Chapter 9

Efficiency of Plasma Gasification Technologies for Hazardous Waste Treatment

Victor Zhovtyansky and Vitas Valinčius

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.74485

Abstract

The chapter is devoted to the development of technologies for the processing of carbonaceous wastes, including hazardous ones, using plasma energy sources. In particular, plasma-steam equipment provides complete environmental safety and high quality of the synthesis gas produced. Its application is also discussed to exclude the risk of environmental pollution by heavy metals, if they are contained in the recycled waste. The advantages of using oxygen instead of air as an additional reagent in gasification processes are underlined. It is shown that the proposed variant of the processing technology corresponds well to the general idea of numerous publications in the world scientific literature, known as the Waste-to-Energy. It has been shown that plasma equipment has significant advantages in terms of the commercialization of processes for the treatment of sewage sludge and some other hazardous waste.

Keywords: waste, biomass, solid fuel, plasma, gasification, plasma torch, syngas, gas engine, distributed energy

1. Introduction

The situation worldwide in the field of environmental protection and efficient energy use is constantly getting worse. In order to more efficiently reduce environmental pollution, traditional thermal methods are not enough. A whole complex of coordinated efficient measures should be applied.

In the last few decades, the problems of carbon-containing materials reforming into synthesis gaseous fuel—mixture CO and H_2—by means of plasma technologies were widely discussed in the scientific literature [1–14]. This syngas can be used for heat or electrical energy production [13].

The European Commission (EC) has defined the European Union (EU) objectives in the energy sector by 2020 (20% less greenhouse gas emissions, at least 20% of the EU's energy resources—renewable energy sources, a 20% reduction of primary energy consumption in the directive EU, COM (2008) 30) [15, 16]. To achieve these objectives, the Member States have to increase the share of renewable energy resources in electricity generation, fuel saving and waste management. At the same time, it should be taken into account about the most effective hazardous waste destruction technology such as a thermal treatment and gasification. Ukraine and Lithuania have approved the Community and follows the most important requirements and procedures of the EU.

It is well known that one of the most effective hazardous waste destruction technologies is a thermal treatment and gasification. However, there exist an entire group of substances any traditional treatment of which causes a threat to the environment and human health. Therefore, present research proposes to develop and implement plasma technology, which allows to remove all waste containing hazardous substances. Plasma decontamination technology of toxic materials allows to create a compact device, which can reliably neutralize all of types of hazardous waste. Such plasma device is characterized by a very high temperature, short reaction time, extreme activation energy, the ability to heat various gases, effective neutralization and independence from fuel sources.

Complete and safe hazardous waste (outdated medications, banned pesticides, plastic gears, pathological waste, container, etc.) removal method is high temperature (plasma) pyrolysis. It is already employed in many countries around the world: USA, Japan, France, Germany, Switzerland, Australia, etc. Many developing countries (India, China, Belarus, etc.) also seek to employ the plasma technology in this area. There is a shortage of detailed technology description in worldwide scientific literature because these research results some times are not made public. Medical wastes from hospitals, dental clinics and other health centers are collected and recycled in about 1500 large companies. Most of them are located in the USA, France, Great Britain and Japan [17, 18].

The interest in plasma technology in the application of harmful substances neutralization processes is huge. For example, the Japanese medical waste management company recently implemented a large project, whose main goal is to transform the infected local medical waste into useful products - glass, metal and syngas.

Environmental safety and technological advantages of plasma using plasma technology for this purpose are noted in many of the papers. However, the most important problem is their energy efficiency, because the efficiency of electricity generation to power the plasma torch (PT) is only about 30% [9]. Thus, in order to achieve the commercialization of such environmentally clean technologies, they need to simultaneously achieve high levels of their energy efficiency. The solution of this problem is also dedicated by this work.

http://dx.doi.org/10.5772/intechopen.74485

2. Waste-to-energy process

Modern technologies of the waste treatment are oriented on the processes of their gasification. It has three interrelated advantages. First of all, the temperature range at which the gasification processes are effectively carried out is quite high and usually exceeds 1000°C. This automatically meets the requirements of the Directive 2000/76/EC [15], according to which the temperature should be maintained at 1100°C in case of incineration of waste containing more than 1% wt. of halogenated organic substances under conditions of chloride. This is necessary for dioxins and furans which are formed at lower temperatures, to be effectively decomposed into HCl.

Second, each local volume of gas produced in the processing has to be kept at this temperature over time ≥2 s. In this case, maximum permissible emission of dioxins and furans to the atmosphere in the refinement products do not exceed 10^{-10} g/m^3 [15]. This is very important as these compounds are among the most toxic ones. In addition, prolonged residence of reagents at high temperature ensures the completeness of gasification processes, and also allows accepting the assumption of equilibrium conditions when performing thermodynamic calculations.

Third, although gasification products must be cooled down quickly to avoid the reverse generation of dioxins and furans, the main energy is accumulated in chemical bonds. Even though syngas cooling leads to some losses of thermal energy, the share of which is small compared to the total energy content which consists of thermal and chemical energies.

Another problem appears when the waste contains in its composition heavy metals; using well known incineration for their utilization leads to formation of ash, which is itself a hazardous waste [19–21]. The latter environmental hazard is particularly dangerous in the case of recycling the sewage sludge of urban wastewater treatment plants [13].

The arc discharged plasma is an effective tool for many types of application including hazardous waste treatment. It is important to notice that there exist several unsolved problems in thermal treatment of sewage sludge area. During the combustion process, solid dispersed particles may be formed from the combustion products. Solid particles may penetrate into the human lungs and can cause serious illnesses. Incomplete combustion may also occur inside the furnace and form new chemicals that may appear to be more toxic than initial material. Therefore, flue gas is cleaned in multicyclones or fiber filters before discharge into the atmosphere. However, such types of filters are expensive and not very effective in the case of fine dispersed particulates. There does not exist means against newly formed hazardous chemicals at all. So the plasma treatment of exhaust combustion products is welcomed. Atmospheric pressure arc plasma is also a promising tool for the synthesis of catalytic coatings which could be successfully employed in the manufacturing of catalyst for flue gas treatment.

3. Plasma processing of hazardous waste

First in Ukraine, full-scale equipment for medical waste processing as well as another hazardous waste has been built by the E.O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine (NASU) and the Institute of Gas, NASU [3, 9]. Its fundamental advantage is using water steam-plasma as a gasification agent, which allows to obtain the gasification products of maximum calorific value. Mode of the equipment operation satisfies all the requirements of the Directive 2000/76/EC [15].

The other type of experimental equipment for destruction of hazardous waste has been installed in Lithuanian Energy Institute (LEI) [11, 14]. It consists of a plasma jet reactor with DC arc plasma source capacity of up to 90 kW. The plasma process uses air, nitrogen, water vapor or their mixtures. The plasma-forming gas flow rate in the reactor reaches up to 2–7 g/s, the average exhaust mass temperature varies from 2800 to 3500 K. Experimental and numerical studies carried out upon the realization of the plasma decomposition process of organic and inorganic substances.

3.1. Plasma sources

Arc plasma torch (PT) is a key element of the equipment. It was made according to the two-electrode axial scheme with hollow copper electrodes. Compressed air and steam are used as the plasma-forming gases. PT ignition is carried out with air and then transition to steam occurs after the heating [9].

The linear DC arc heater was produced in LEI for heating air, nitrogen, steam or their mixtures up to 7000 K. It was connected to the reactor vessel. By achieving gas temperature over 4000 K, molecules of hazardous substances and waste decay to atoms, radicals, electrons and ions so that it appears ability to obtain simple combination of harmless chemicals. Several configurations of linear DC PT with hot cathode and step-formed anode were considered. As a sample, it could be mentioned PT 70 kW of power, with radial and tangential injection designed especially for the production of non-equilibrium plasma jet. Its analog was described elsewhere [22]. The novel PT (**Figure 1**) was manufactured and applied for the treatment of hazardous organic and inorganic compounds. It consists of a button type hafnium cathode, transitional copper anode for arc initiation 3, neutrode 5, insulation rings and step-formed copper anode 7. To increase the angular velocity of arc rotation, magnetic stabilization of flow was applied employing the coil 8 [22].

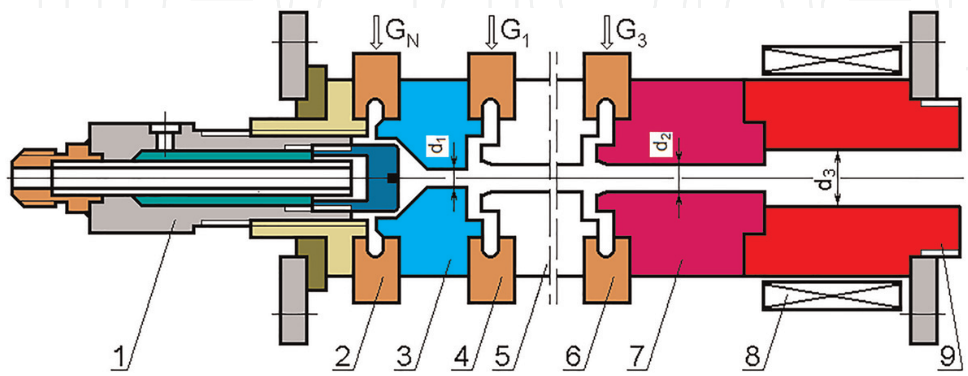

Figure 1. Schematic presentation of linear DC plasma torch. 1—Cathode junction with hafnium emitter; 2, 4, 6—Insulating rings with gas injection; 3—Intermediate anode; 5—Neutrode; 7, 9—Step-formed anode; 8—Magnetic coil.

http://dx.doi.org/10.5772/intechopen.74485

A new PT is employed for heating the material that is injected into the reaction arc chamber. Both average and local heat losses of PT elements are necessary to know when the device is operating under extreme conditions to select operating and cooling regimes. Operating characteristics of the PT plasma flow and parameters were determined from the heat conservation calculations while measuring voltage drop, gas flow rate and arc current strength in the circuit. The preference has been given to the PT with neutral, fixed average arc length and step-formed copper electrode [22]. This enabled to reduce arc shunting after anode step and ensured the stability of length of the arc in the wide diapason of gas flow rates and current variation. The employed plasma source also is different comparing to ordinary plasma torches with the conical expanded anode. The anode step also serves for reduction of the pressure drop in the discharge channel and to fix the arc in the stable position. The total PT length is 0.25 m, the insular part anode diameter is 0.03 m and the diameter of extended part of the anode is 0.04 m. The neutrode makes separate neutral section of the torch and is isolated from the anode. It is located between insulating rings made of thermal resistant glass textolite. Each ring is also used for tangential air supply and contains a pair of tangential-oriented blowholes (as G_N, G_1 and G_3 in **Figure 1**) for the arc stabilization. The experimental equipment for producing arc plasma is comprised of rectifier for power supply, gas supply, water-cooling systems and airing devices.

The modified similarity theory has been applied for the analysis of operating and thermal characteristics and result generalization [22–24]. Voltage–current characteristic (VCC) of PT were generalized employing criterial equations and following expressions were established:

$$\frac{Ud_2}{I} = 1350\left(\frac{I^2}{Gd_2}\right)^{-0.55}\left(\frac{G}{d_2}\right)^{-0.14}(pd_2)^0. \tag{1}$$

PG performance and thermal characteristics can be evaluated by its efficiency η indicating what part of generated energy is transferred to gas:

$$\eta = GH(UI). \tag{2}$$

Generalization of the TC of PG is similar to generalization of the electric characteristic:

$$\frac{1-\eta}{\eta} = 5.5{*}10^{-3}\left(\frac{I^2}{Gd_2}\right)^{0.22}\left(\frac{G}{d_2}\right)^{-0.12}(pd_2)^0\left(\frac{l}{d}\right)^0. \tag{3}$$

Here U is arc voltage, I is arc current, G is total gas flow rate, d_2 is anode diameter and p is pressure. The value of η may be presented also as the Stanton number [23]:

$$\frac{1-\eta}{\eta} = \frac{4l}{d_2}St. \tag{4}$$

The research concludes that PT VCC depends on the following main factors: (i) radial and tangential injection of plasma-forming gas; (ii) gas flow rate of plasma-forming gas to produce the desired arc; (iii) arc chamber geometry and (iv) gas composition. The first factor was evaluated during the experimental investigation of gas flow rate at the constant and various values of PT. In the present and previous [22] studies when the radial injection is not applied, operating characteristics were observed as decreasing in the current range between 150 and 250 A. This follows as a result of dropping electric field intensity which linearly depends on the arc current. It was also established that voltage drop and electric field intensity linearly decrease with increasing of gas flow rate in the range of 7–10 $\times$ 10^{-3} and 5–8 $\times$ 10^{-3} kg s^{-1}. When the radial and tangential injection in different locations is used, the arc is strongly turbulized and a possibility to heat up much larger amount of gas in the PT of reduced dimensions is available. Consequently, the voltage drop in such PT increases up to 70% and the possibility for better control of plasma-forming process appears.

When tangential injection of plasma-forming gas is applied inside the PT anode, the character of operating characteristics is slightly dropping or remains as stabile. The impact of gas flow rate, anode diameter and arc current on plasma generated electric characteristics and thermal efficiency for similar PT are described in Refs. [22, 23, 25]. It is important to notice that static PT characteristics may be also slightly rising with increase of arc current strength.

The present measurements over 120 experiments were carried out varying with the help of resistors arc current strength and injected air flow rate G_1 and G_3. Some geometrical PG characteristics and ranges of experiments carried out are summarized in **Table 1**.

3.2. Plasma chemical reactors

Technologically, the conversion process is carried out in a flow reactor. It has a metal case and is lined with the layer of fireproof and heat-insulating materials on the inside (**Figure 2**). PT

Power, P (kW)	33–78
Arc current, U (A)	175–245
Arc voltage, I	160–335
Cooling water flow rate, Gv (kg s^{-1})	0.16–0.18
Water temperature increment (deg):	
plasma torch	15–23
cathode	1.1–1.53
ignition section	1.08–2.16
neutrode	–
anode	13.0–19.3
Source gas flow rate (kg s^{-1}):	
cathode, G_N	0.54–1.0
neutrode, G_1	–
anode, G_2	1.85–7.6
Plasma jet average mass temperature (K)	3460–5200

Table 1. Plasma source technical parameters.

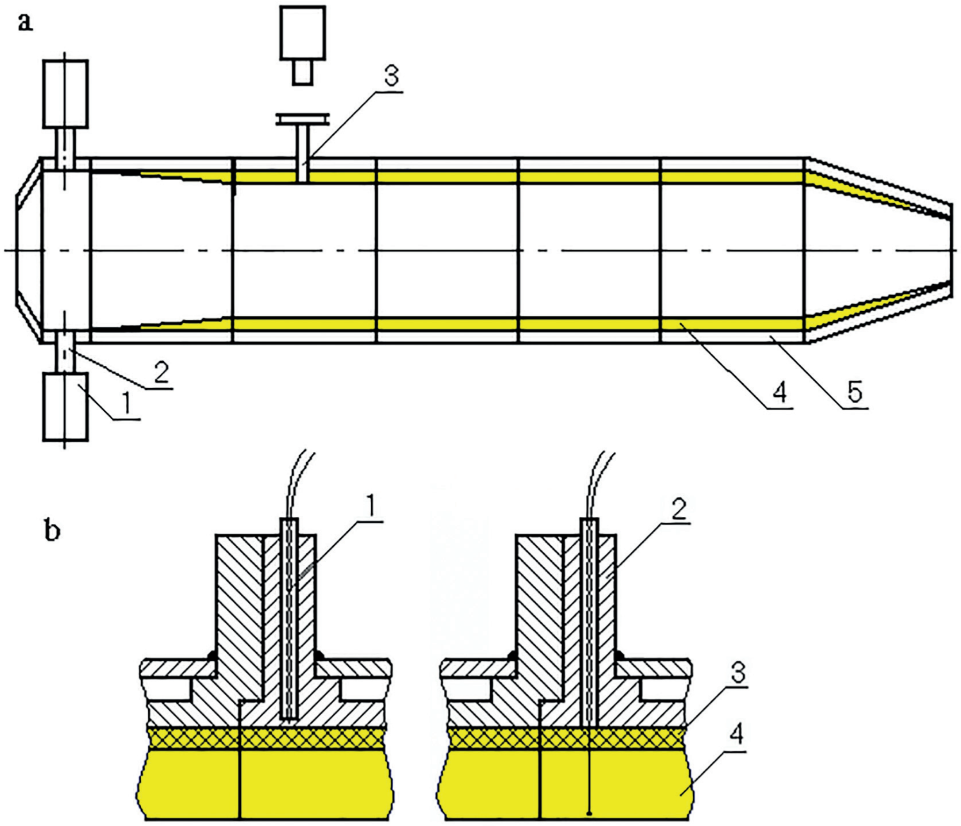

Figure 2. Schematic presentation of plasma jet reactor for treatment hazardous waste. (a) Stream reactor with: 1—Plasma torch; 2—Plasma torch and feeder connecting section; 3—Window for observation and measurement; 4—Layer of Zr_2O_3; 5—Cooling section (five units). (b) Construction of thermocouple's junction: 1—Thermocouple; 2—Frame; 3—Layer of insulating cover; 4—layer of ceramic cover.

electrical power reaches up to 160 kW with efficiency coefficient = 0.7–0.8. The equipment also includes lock-chamber for the periodic load of the packed medical waste, steam generator, power supply of up to 500 volts and a current up to 350 A, as well as the system for the gas quenching and cleaning. General view of equipment as well as PT is shown in paper [9].

The lock-chamber for medical wasteload is located in the upper part of the reactor. Unit management does not involve the full loading of the total reactor space with wastes. This is important for gasification products, if they move through a thick layer of raw materials, not to be cooled below 1100°C [15].

Table 2 presents the composition of the basic gasification products obtained from the medical waste in the equipment for plasma-steam gasification [9]. In these experiments, organic wastes of such average composition have been studied: 60% of cellulose $C_6H_{10}O_5$ + 30% of plastics based on polyethylene ($–CH_2–CH_2–$)n + 10% water.

Components	H_2	CH_4	CO	CO_2	C_2H_4	C_2H_2	C_3H_6	H_2S	H_2O	Other
%. vol.	49.89	1.99	35.25	2.52	3.37	3.92	0.45	0.13	1.92	0.63

Table 2. Basic gasification products composition obtained from medical waste.

The main physical result of this experimental exploration was a possibility of self-power supply by syngas with gas-diesel engine system taking into account even low efficiency of electricity production ~30%. This fact was verified in Section 4.2 on the ground of thermodynamic calculations.

In general, the previous experience of using this equipment has confirmed the correctness of the basic technical solutions laid down therein. However, it also revealed some shortcomings of individual design solutions. They demand the revision process of further development. In particular, this applies to the high temperature thermal insulation of the reactor [9].

Three different plasma chemical reactors were designed in LEI:

- straight stream reactor for flue gas treatment;
- curved stream reactor for the treatment of gaseous, liquid and solid substances with small solid dispersed particles and
- steady ARC volume reactor, devoted for incineration of wide range of waste.

The last-mentioned is under reconstruction.

We have assumed the plasma flow has been characterized as optically thin. The transport coefficients and thermodynamic properties depend only on the temperature and pressure. The plasma flow in the reactor is also characterized with extremely high temperature gradients and recirculating turbulent flow with wall confinement. The flow inside the chamber was separated. Heat transfer characteristics in the entrance region of the reactor in this case of sudden expansion for the region of $x/d < 0.4$ could be described by the following equations:

$$Nu_{fd} = 0.006\mathrm{Re}_{fd}^{0.86}. \tag{5}$$

For the region of $x/d > 0.4$ described by the equation for entrance region of the pipe:

$$\mathrm{Nu}_{\mathrm{fd}} = 0.0256\mathrm{Re}_{\mathrm{fd}}^{0.8}\varepsilon_{1}. \tag{6}$$

Here ε_l is the entrance factor, equal:

$$\varepsilon_l = 1.48(x/d)^{-0.15}. \tag{7}$$

Nu and Re are Nusselt and Reynolds criterions, respectively. Index *fd* means that Nu and Re are calculated according to the flow conditions in the entrance and reactor channel diameter.

4. Plasma application in sewage sludge treatment

During sewage treatment, the main pollutants are separated as sewage sludge. Depending on the original pollution load of the water being treated, they may include the heavy metals in

http://dx.doi.org/10.5772/intechopen.74485

their composition. The Kyiv wastewater treatment plant (known as Bortnychi station of aeration) processes municipal and industrial sewage and run-off rain water. It accepts 9000 m^3 wastewater per day on an average. At present, 9 million tone of sewage sludge are accumulated on its territory [13].

Centralized wastewater treatment plants in Lithuania produce relatively small amounts of sewage sludge. The annual amount of dry sewage sludge produced in Lithuania is up to 50 thousand tons per year.

The special problem of this waste is heavy metals in its compound [16, 17]. The presence of these pollutants prevents the burial of sewage sludge and substantially limits its use in agriculture and forestry. A similar situation occurs when certain wastes (e.g., industrial, medical, military and sewage sludge) are destroyed in special devices known as incinerators, which leads to the formation of relatively high toxic waste in ash. Toxic residues (ash, slag, sediment of filters and sedimentation tanks) can be easily placed on landfills in case they were first immobilized and converted to non-leachable products. If these residues are heated to a very high temperature, then their main components, including minerals and toxic heavy metals, melt and take on a glassy appearance. This requires temperatures above 1700 K, which are not available in the most incinerators, but are easily achieved in plasma reactors [21]. The system of plasma vitrification of ash produces a chemically stable and mechanically strong substrate. After vitrification, this mineral product looks like a vitreous, similar in structure to basalt lava (even superior to basalt by mechanical strength); its main components are oxides of silicon, aluminum and calcium in the form of chemically inactive compounds that are resistant to washing. The effectiveness of this technology is convincingly confirmed by the data on the example of vitrification of the ash residue in a medical incinerator, given in Ref. [21].

A simple empirical estimate of the energy inputs required for the vitrification process is given in Ref. [26]:

$$M(kg) = 0.35P(kWh), \tag{8}$$

where M is the mass of the vitrified product and P is the electrical energy consumed in the process. It is quite simple and allows you to calculate the energy required for the gasifier, regardless of the thermodynamic calculations associated with the conversion of carbon-containing raw materials.

4.1. Laboratory experiment

The equipment for hazardous waste processing created at the Institute of Gas, NASU was presented shortly above. Its fundamental advantage is using of water steam-plasma PT up to 160 kW of capacity. Nevertheless, such powerful and complex equipment cannot be used for laboratory studies to optimize the gasification processes of different types of carbon-containing raw materials. That is why relatively low-power industrial steam PT “Multiplaz 3500” up to 3.5 kW has been used in this research.

Components	H_2	CO	CO_2	CH_4
%. vol.	71.8	0.1	24.7	0.4

Table 3. Basic gasification products composition obtained from sewage sludge.

Quartz tube of inner diameter 3.2 cm and a length of 13 cm was used as a reactor model. It placed a portion of sewage sludge to be studied in the process of gasification. Aggregate data on the composition of treated dry products of gasification are presented in **Table 3** [13].

With these data, an equation for the reaction involving carbon, hydrogen, oxygen and organic matter was determined:

$$\mathrm{C}H_{2.483}O_{0.530} + 1.334\ H_2O = 2.549H_2 + 0.111CO + 0.876CO_2 + 0.013CH_4. \tag{9}$$

Gross equation of sewage sludge in this reaction correlates well with the results of independent chemical study in Ukraine for their composition.

Analyzing the results of this experiment, it should be noted its main disadvantage associated with the overall low efficiency of the gasification process, despite even a relatively high yield of hydrogen. Indeed, most of the carbon in process (9) is directed to the production of a ballast gas CO_2, rather than a combustible CO. Thus, this experiment cannot be considered as too successful in terms of achieving the ultimate goal of the process – high energy efficiency.

The main reason for this result appears to be the low wall temperature of the reactor-quartz tube, which in these studies was 430–480°C. The two processes seem to contribute for the syngas production: the actual steam-plasma gasification of the raw material on the tube axis, where the temperature determined by the PT jet is quite high, and the so-called water gas shift reaction at the walls of the tube.

$$CO + \mathrm{H_2O} \rightarrow \mathrm{H_2} + \mathrm{CO_2}. \tag{10}$$

The optimal temperature for this reaction is just about 500°C [27]. This assumption is also supported by the very high content of CO_2 in the reaction products in a small diameter quartz tube (**Table 3**), if compared with our experimental data in the full-scale reactor presented in **Table 2**.

Equally important and negative factor was also the low reaction rate of carbon in such a system, which exponentially depends on the temperature. As a result, a significant part of steam as gasifying agent passes a small reactor, not reacting with the raw material, which in general predetermines the low energy efficiency of the process.

Already in appearance of the gross equation, it follows that sewage sludge should have good energy characteristics, based on the ratio of the hydrogen and oxygen components in its composition [27]. In the further basic thermodynamic estimates, we selected a simple and convenient for estimation the gross sewage sludge equation in the form of $CH_{2.5}O_{0.5}$ for which an analysis of the processes of plasma-steam gasification is performed later.

4.2. Thermodynamic calculation of the gasification process using plasma technologies

4.2.1. Generalized reaction of gasification

At present, quite a lot of software tools have been developed and used for quantitative analysis of gasification processes. However, with all the advantages of numerical calculations, such publications leave "in shadow" basic physical and chemical regularities. Just the knowledge of their characteristics built a clear understanding of the analyzed process. In reality, the basis of the quantitative description of gasification lie very simple thermodynamic relations arising from the laws of Hess used in thermochemistry [28]. It should be borne in mind only the features associated with the operation of the plasma source [29].

Following Refs. [29–31], the process of plasma-steam gasification can be represented by the gross equation in a sufficiently general form:

$$CH_xO_y + wH_2O + mO_2 = n_1H_2 + n_2CO + n_3CO_2 + n_4H_2O + n_5CH_4 + n_6C + Q_{TR}, \qquad (11)$$

where $Q_{TR} = Q_R + \Delta Q$ is the total thermal energy that is released as a result of the chemical reactions Q_R and due to some additional source of heat energy ΔQ (so far we do not necessarily associate it with the energy of the plasma jet Q_{PL}), so that the reaction mixture reaches the desired temperature T_P of the gasification products, w and m—the amount of water and oxygen, per 1 kmol of waste, n_1, n_2, n_3, n_4, n_5 and n_6 are the coefficients for the corresponding reaction products. Among the latter are gases, most often obtained in the composition of gasification products and soot. In this formula, the energy term in the form presented was introduced in our paper [29]. It allows to distinguish the role of an additional source of energy ΔQ in viewpoint of achieving the optimal, predictably perceived, temperature T_P of the gasification process.

The "ideal" process of plasma-steam gasification would correspond to the case when only H_2 and CO would be present on the right side. Formally, it is possible to make many options of reaction (11) with various stoichiometric coefficients, including the relevant "ideal" process. However, in accordance with the second law of thermodynamics, nature chooses only such a path and the completion of the varying reactions, in which the principle of maximum entropy is realized:

$$dS \geq dQ/T. \qquad (12)$$

Special software—"TERRA" thermodynamic calculations system is used for the conversion processes quantitative analysis with a glance of the accompanying reactions [32]. It also allows to determine the necessary amount of energy expenditure for carrying out reactions.

4.2.2. Plasma-steam gasification

Analysis of the process of plasma-steam gasification was made on a more optimal than (9) reaction:

$$CH_{2.5}O_{0.5} + 0.5H_2O = CO + 1.75H_2 \quad + Q_{TR}. \tag{13}$$

The heat of combustion of sewage sludge Q_{LSS} required to determine the energy of the process is determined on the basis of Mendeleev's Eq. [27]:

$$Q_{lSS} = -100\cdot(81\cdot c_C + 246\cdot c_H - 26\cdot(c_O - c_S) - 6\cdot c_W\ )\cdot 4.19\ kJ/kg, \tag{14}$$

where $c_{C,}$ $c_{H,}$ $c_{O,}$ c_S and c_W are mass fractions of carbon, hydrogen, oxygen, sulfur and water. (Mendeleev's equation is an analog of the relations known in the Western scientific literature as Dulong or Milne equation.) As may be shown, this heat of combustion of sewage sludge is Q_{LSS} = −25.68 MJ/kg [33]. Following the law of Hess, its enthalpy of formation is $\Delta H^0_{CH2.5O0.5}$ = −76.8 kJ/kg [33].

The thermodynamic analysis of the sewage sludge conversion process carried out in the TERRA software [32] allows to determine the composition of its gasification products as a function of temperature. As it turned out, both for the reaction (12) and for other considered reactions, it is characterized by the practical completion of the gasification processes at 1250 K. More strictly, the mass fraction of the traces of CO_2, H_2O and CH_4 among the products of gasification at this temperature does not exceed 1–2%. As it turned out, the energy $Q_{PL}(T)$, which must be additionally introduced with a plasma torch per 1 kg of reagent mass in (12), to reach this temperature, is 0.785 kWh/kg. This parameter allows to determine the productivity of the gasifier at a given power of the PT.

Knowing the calorific values for CO and H_2, as well as the composition of the products obtained in the reaction (12), it is easy to determine the calorific value of the resulting syngas in this process W_{SG} = 6.23 kWh/kg. It allows to define the energy output of the gasification plant and its energy efficiency on the basis of a comparison with the specific energy Q_{PL} introduced into the reactor.

The value W_{SG} significantly exceeds the electricity consumption 0.785 kWh/kg by steam PT to produce 1 kg of syngas. Thus, even taking into account the relatively low efficiency of $\eta_{EE} \sim 0.3$ of electricity generation, the energy consumption is much lower than the level of energy of syngas produced. Indeed, taking into account also the efficiency of the PT at $\eta_{PL} = 0.8$, this is enough to ensure the operation of the PT, since it exceeds the value of ΔQ = 0.785 kWh/kg:

$$W_{SG}\cdot\eta_{EE}\cdot\eta_{PL} = 6.23 \times 0.3 \times 0.8 = 1.5\ kWh/kg > 0.785\ kWh/kg. \tag{15}$$

It is good preconditions for the energy self-sufficiency of the sewage sludge processing and the production of additional energy to compensate the role of raw materials moisture and ash residue vitrification or for the production of electricity for external consumers.

4.2.3. Plasma-steam-oxygen gasification in stoichiometric mode

Significant increase of conversion efficiency can be achieved by the addition of oxygen into the process. At the first stage, an "ideal" conversion reaction was considered, in which the number of reagents, in contrast to (13), contained also oxygen, and among the reaction products syngas components only were present:

$$CH_{2.5}O_{0.5} + KH_2O + LO_2 \rightarrow CO + MH_2 + Q_{TR} \tag{16}$$

where K, L, M are coefficients that determine the content of components such as steam and oxygen, as well as the hydrogen one in the reaction products, respectively, under the stoichiometric reaction with respect to syngas production. Thus this reaction is stoichiometric as well as (13) for obtaining products of gasification as synthesis gas only. Nevertheless it has the most wide functional possibilities to achieve the best index of energy efficiency of the process as it allows varying the composition of the gasification agent. In determining the energy efficiency, naturally, the consumption of energy for oxygen production should also be taken into account. The range of possible specific energy consumption in the technological process of obtaining the oxygen itself is chosen as P_{O2} = 0.35–1 kWh/m^3. The first one corresponds to promising technologies, the second one is realistic today. Quantitative index of energy efficiency of the conversion process is the ratio

$$\eta = \left(\mathrm{P}_{PL}^{\mathrm{C}} + \mathrm{PO}_2\right)/W_{SG}, \tag{17}$$

where $\mathrm{P}_{\mathrm{PL}}^{\mathrm{C}} = \Delta Q/0.8$ is the electricity consumption for the production of plasma jet by efficiency of ~ 0.8 and for oxygen – P_{O2}. W_{SG} is the heat energy of syngas from 1 kg of the original raw mixture. In this form, it fully corresponds to the definition of energy saving (or energy efficiency) as energy costs (here, $P_{PL}{}^J + P_{O2}$) per unit productivity (here the product is syngas of energy W_{SG}).

The value of L = 0 in reaction (16) corresponds to the plasma-steam gasification (13), and the case ΔQ = 0 is usual steam-oxygen technology, although their opposition does not make sense. Indeed, from the point of view of the process chemistry, in both cases, oxygen atoms, characteristic of these technologies, and hydrogen atoms, originally included in the gasified sewage sludge, are present in the reaction. For the noted limit values of L, the coefficient K takes the values K_{max} = 0.5 and K_{min} = 0, respectively. However, generally speaking, the reactions (16) can also correspond to the intermediate values of the coefficients K and L. Simple functions are determined on the basis of mass balances in reaction (16):

for oxygen

$$1{\cdot}0.5 + K + 2L = 1, \textit{or } L = 0.25 - 0.5K; \tag{18}$$

for hydrogen

$$1{\cdot}2.5 + 2K = 2M, \textit{or } M = 1.25 + K. \tag{19}$$

For clarity, the function (18), which characterizes the oxygen content of L as a function of the amount of steam K introduced by the PT, is shown in **Figure 3** as line 1. Line 4 represents the thermal power introduced into the reactor by a plasma jet at its nominal enthalpy of H_{PL} = 3.6 kW·h/kg in accordance with equation

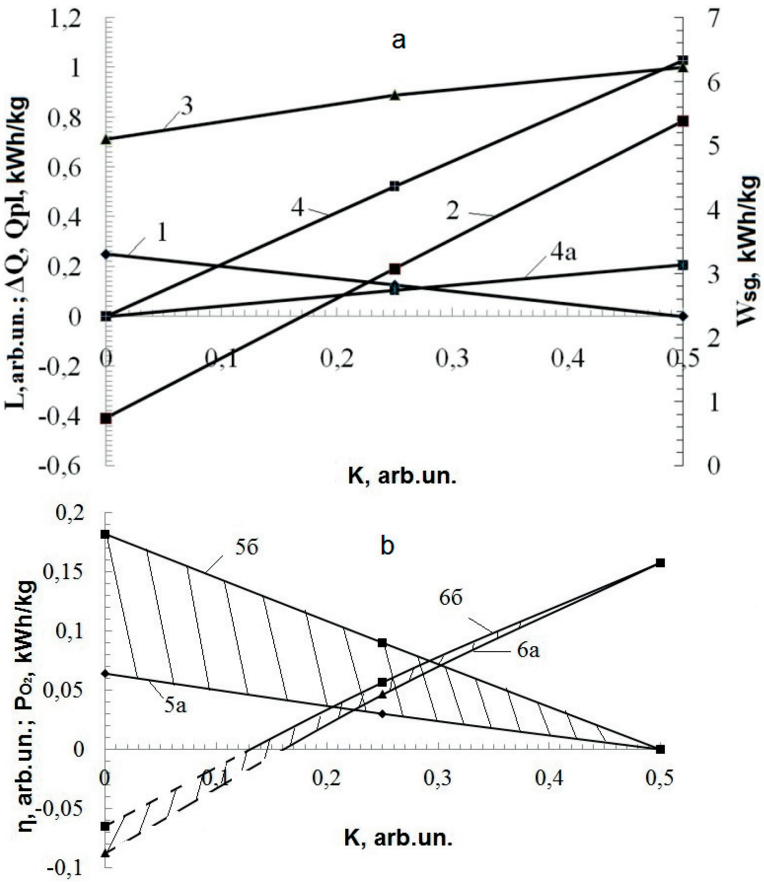

Figure 3. The main regularities characterizing the stoichiometric mode of gasification of the sewage sludge in the function of the amount of water introduced into the reaction *K* with plasma-steam jet – molar and energy ratios (a) and energy consumption for oxygen production and energy efficiency indicators of process (b): 1—oxygen content *L* introduced into the reactor; 2—additional energy ΔQ, which should be introduced in volume to achieve the operating temperature; 3—the energy of the producing syngas W_{SG}; 4, 4a—the energy introduced by the steam-plasma jet Q_{PL} with its enthalpy $H_{PL} = 3.6$ and 0.72 kWh/kg, respectively; 5a and 5b—energy consumption for oxygen production at a specific consumption of energy 0.35 and 1 kWh/Nm^3, respectively; 6a and 6b—indicators of energy efficiency of the process at the corresponding specified energy consumption for the production of oxygen.

$$Q_{PL} = H_{PL} mH_2O, \tag{20}$$

where mH_2O corresponds to the mass of water in the jet injected per kg of reagents. This enthalpy value corresponds to the moderate operating mode of the PT used in Ref. [9]. In principle, the higher values of plasma enthalpy, corresponding to the forced operating regime of the steam PT, can be achieved.

It can be concluded that the introduction of oxygen in the stoichiometric mode of gasification with the use of plasma technologies corresponds to an increase in the energy efficiency of the process. As it follows from **Figure 3b**, the maximum value η in the process (which corresponds to the highest value of the additional energy ΔQ and, consequently, the worst energy efficiency) occurs exactly when the oxygen content is $L = 0$, for which $K = 0.5$ corresponds—that is, on the right side of each graph. On the contrary, the value η decreases with a gradual increase of the oxygen content *L* (i.e., moving to the left along the abscissa).

http://dx.doi.org/10.5772/intechopen.74485

Area $K < 0.17$ corresponds the negative values $\Delta Q < 0$ (**Figure 3**); this means that excess heat energy is released in the reaction zone, which can be used for the ash residue's vitrification. The level of energy consumption for this need is difficult to determine in general terms, but empirical ratio (13) is known for them. In this area, lines 6 characterizing the level of energy efficiency of the process η are indicated by a dashed line. This is emphasized by the fact that here the energy costs for maintaining the gasification process are negative. In other words, there is an energy release.

In the absence of a PT, the stoichiometric gasification regime according to the reaction (15) is realized for a single value $K_0 = 0.17$, corresponding to the intersection of line 2, which characterizes the required energy level ΔQ with the coordinate axis. It, in turn, corresponds to the moisture content of sewage sludge of about 10%, if it is determined from the composition of the reagents on the left side of the reaction (15). This moisture value is characteristic just for the conditioning of sewage sludge, which are currently dried with the help of those or other drying technologies.

However, the range of values $K = 0.17$ and near it for practical operation of the gasifier should be excluded, because the software TERRA reveals a significant soot formation, which makes it unacceptable for gasification. Thus, solving also the problem of obtaining more high quality syngas, it is expedient to move along line 2 to its maximum value corresponding to the stoichiometric regime at $K = 0.5$ (**Figure 3**). The results obtained are presented in **Table 4**. As can be concluded, an increase in the amount of water introduced into the process L is twice, corresponds to a worsening of energy efficiency of the conversion process η by a factor three.

4.2.4. Non-stoichiometric mode of plasma-steam-oxygen gasification

The introduction of a significant amount of energy with a plasma jet markedly worsens the indicator of the energy efficiency of the plant, as follows from **Figure 3b** and **Table 4**. Therefore, it is of interest to compare it with the non-stoichiometric regime, which can be easily

Parameter		K, arb.un.	
		0.25	0.5
L, arb.un.		0.125	0
ΔQ, kWh/kg		0.19	0.785
P_{PL}^{C}, кВт·ч/кг		0.24	0.98
P_{O2}, kWh/kg	p_{O2} = 0.35 kWh/Nm^3	0.03	0
	p_{O2} = 1 kWh/Nm^3	0.09	0
$W_{CГ}$, kWh/kg		5.79	6.23
η, arb.un.	p_{O2} = 0.35 kWh/Nm^3	0.046	0.15
	p_{O2} = 1 kWh/Nm^3	0.057	0.16

Table 4. Calculated parameters characterizing the stoichiometric process of conversion of sewage sludge at its humidity of 10% to synthesis gas using plasma technology, depending on the additional amount of water vapor introduced with the plasma jet.

realized for the same value of L_0 = 0.165, as in the stoichiometric regime at the point K_0 = 0.17, but at K > 0.17. Therefore, it is advisable to introduce excess oxygen into the reactor.

In this case, in order to optimize the plasma-steam gasification process of sewage sludge, the next reaction was analyzed:

$$CH_{2.5}O_{0.5} + KH_2O + LO_2 \rightarrow CO + MH_2 + ECO_2 + DH_2O + Q_{TR}. \quad (21)$$

This gasification mode is called "non-stoichiometric", as there are the products of partial combustion of sewage sludge—CO_2 and H_2O—among the products of gasification. In determining the parameters of the process in the non-stoichiometric mode of gasification, it should be taken into account that, in addition to the syngas, the ballast components are formed from the unit mass of the initial reagents. In other words, the correction factor should be taken:

$$W^*_{SG} = [(mCO + mH_2)/(mCO + mH_2 + mH_2O)]W_{SG} = k_{NS}W_{SG}, \quad (22)$$

where k_{NS} is the non-stoichiometric coefficient.

Recall that, in principle, it is possible to compose many variants of the reaction (21) with the different stoichiometric coefficients. However, in fact, only those are actually realized where maximum entropy principle is satisfied (see Eq. (12)). Examples of the resulting compositions of gasification products are shown in **Table 5**.

Using these data, the parameters of non-stoichiometric gasification regimes for K = 0.25 and 0.5 were calculated (**Table 6**).

Analyzing the results presented in **Table 6**, it should be borne in mind that they are not energetically self-consistent. Indeed, with an oxygen content L_0 = 0.165, a relatively small additional thermal energy ΔQ = 0.04–0.09 kWh/kg is required. **Table 6** also shows the energy introduced with a jet of a PT operating in our ordinary energetic mode with enthalpy H_{PL} = 3.6 kWh/kg [9] and – for comparisons – in a much less intense mode H_{PL} = 0.72 kWh/kg. One can conclude by comparing the values of ΔQ and H_{PL} between each other, that in this regime one can confine ourselves to a low-power PT. Otherwise, the excess energy of the plasma torch can be used to vitrify the ash residue. Thus, the final analysis causes a significant decrease in the value η compared with the data in **Table 4**. Here it should be taken into account that when working with moist sewage sludge, the energy introduced by the PT is proportional to ΔK = K - K_0. The introduced thermal energy levels at K = 0.5 exceed the noted values ΔQ and, in the absence of

The water content in reagents, the mole fraction of K	Composition of gasification products, wt.			
	CO	H_2	CO_2	H_2O
0.25	0.84	0.089	0.034	0.032
0.5	0,.69	0.083	0.11	0.117

Table 5. Composition of gasification products in non-stoichiometric mode with oxygen content L_0 = 0.165 according to the calculated data in the TERRA software.

http://dx.doi.org/10.5772/intechopen.74485

energy consumption for vitrification, would lead to overheating of the internal volume of the gasifier.

The consumption of electrical energy for the production of a plasma jet with a much lower enthalpy—0.72 kWh/kg is also shown in **Figure 3a**. Without even carrying out detailed calculations, it can be concluded that the use of a less powerful PT would lead to an improvement of the energy efficiency of the process, since it is the level of energy expenditure for the operation of the PT that determines its effectiveness.

The calculated data of **Table 6** can be useful for assessing the efficiency of the sewage sludge gasification installation, depending on the presence of the mineral mass, which requires vitrification, in its composition. For this, it should be taken into account that at $K = 0.5$, the next excess energy P is introduced into reactor:

$$P = (Q_{PL} - \Delta Q)/0.8 = (0.58 - 0.09)/0.8 = 0.6\ \text{kWh/kg} \tag{23}$$

(when recalculating to electrical energy to power PT). To determine the permissible content of the mineral part in the initial sewage sludge, it is necessary to use the relation (7). If there is a mineral mass in the composition of sewage sludge at a rate of M per 1 kg, the amount of excess energy produced is converted into electric energy, which will be $P(1 - M)$, and it, in turn, can be consumed for vitrification according to (7). Hence we can define M:

$$M(kg) = 0.35P(1 - M), \tag{24}$$

where the difference in parentheses characterizes the amount of syngas obtained from 1 kg of the mixture. It follows that $M = 0.17$ kg. Thus, the data of the last column of **Table 6** for the

Parameter		**K, arb. un.**	
		0.25	**0.5**
L_0, arb. un.		0.165	0.165
ΔQ, kWh/kg		0.04	0.09
Q_{PL}, kWh/kg	H_{PL} = 3.6 kWh/kg	0.16	0.58
	H_{PL} = 0.72 kWh/kg	0.03	0.12
P_{O2}, kWh	p_{O2} = 0.35 kWh/Nm^3	0.04	0.035
	p_{O2} = 1 kWh/Nm^3	0.114	0.1
k_{NS}, arb. un.		0.934	0.807
W_{SG}*, kWh/kg		5.44	5.11
η, arb. un.	p_{O2} = 0.35 kWh/Nm^3	0.015	0.023
	p_{O2} = 1 kWh/Nm^3	0.028	0.033

Table 6. Calculated parameters characterizing the non-stoichiometric process of sewage sludge conversion with its 10% humidity in syngas with oxygen content L_0 = 0.165 using plasma technology depending on the amount of water steam $K > K_0$ introduced with plasma jet.

index of the energy efficiency of the gasification equipment are valid up to 17% of the mineral content in sewage sludge to be vitrified.

A more rigorous problem of the non-stoichiometric gasification regime, self-consistent with respect to energy consumption, is also considered. It was solved on the basis of varying the values of L in the reaction (21) for a given value of K. The value of L was determined at which the compensation of the emerging thermal energy deficit ΔQ is attained due to the energy of the plasma jet introduced with the indicated quantity K of water steam at a certain enthalpy. In other words, it was determined at which values of L the condition $\Delta Q(L) - Q_{PL} = 0$ is reached.

The main regularities, which ultimately represent the efficiency of the non-stoichiometric gasification process with a small enthalpy of H_{PL} = 0.72 kWh/kg of the plasma jet and in its absence, that is, for wet bottom sludge are shown in **Figure 4**.

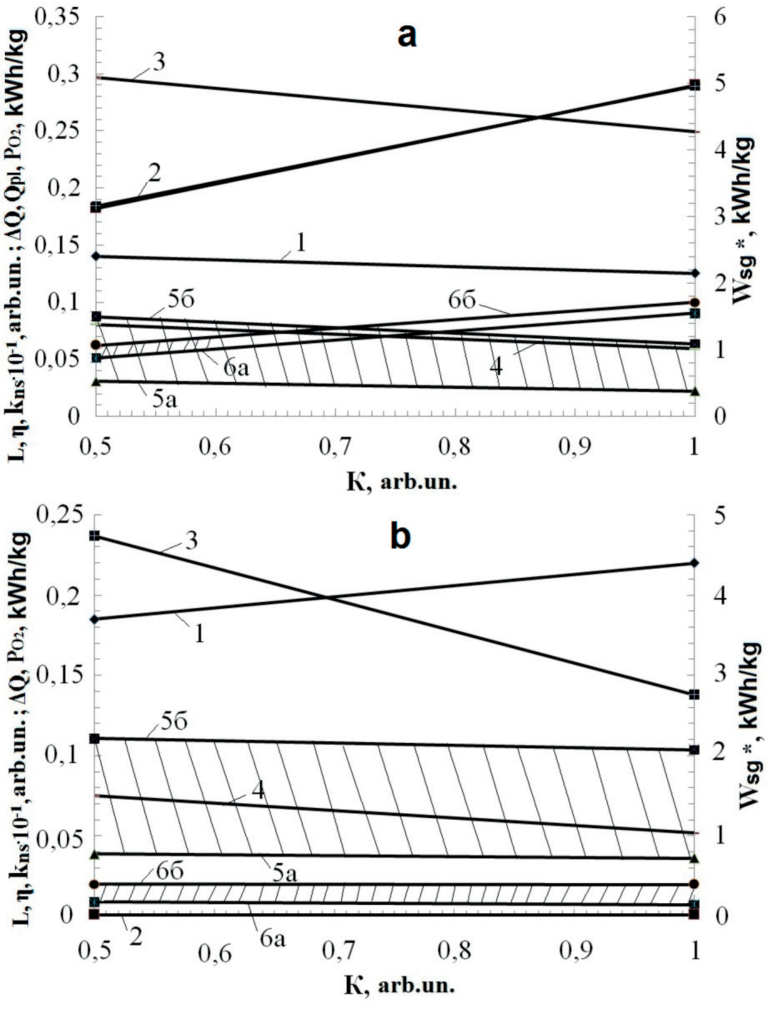

Figure 4. The main regularities characterizing the energy efficiency of non-stoichiometric modes of sewage sludge gasification as a function of the amount of water vapor K introduced into the reaction with the enthalpy of the plasma jet H_{PL} = 0.72 kWh/kg (a), and also, in its absence, for wet sewage sludge (b): 1—the oxygen content L introduced into the reactor; 2—additional energy ΔQ, which should be introduced into the volume to reach the operating temperature, equal to the energy introduced by the steam-plasma jet Q_{PL} (the latter—with the exception of wet sewage sludge); 3—the energy of the syngas W_{SG}*; 4—coefficient of nonstoichiometryk_{NS}; 5a and 5b—energy consumption for the production of oxygen at a specific consumption of 0.35 and 1 kWh/Nm^3, respectively; 6a and 6b—energy efficiency index of the process at the indicated energy inputs for the production of oxygen, respectively.

In the first of these cases, the energy efficiency index in the entire range of moisture content K in the reacting mixture does not exceed 0.1 (**Figure 4a**). Even better is the efficiency index of the steam-gasification, that is, in the second case, when its value does not exceed 0.05. However, one should realize that in the reactor space the vitrification and gasification zones are not so separated in space that some of the energy of the plasma jet is not consumed by the gasification processes. Therefore, we believe that, in general, the proposed technology can ensure the energy efficiency of the gasification process for sewage sludge with an index not worse than 0.1.

Thus, practically all cases presented in **Figure 4**, the consumption of syngas for the electricity generation by means of a gas-diesel power station is only a fraction of the total volume of its production

$$PO_2 + \Delta Q_{PL}/0.8)/\eta_{EE} = \eta W^*_{SG}/\eta_{EE} \approx 0.1\eta W^*_{SG}/0.3 \approx 0.33 W^*_{SG}. \quad (25)$$

In the variant represented by the last equation, this part is only 30% of the energy for the synthesis gas obtained (in deriving these relations, Eq. (17) was used). Accordingly, the remaining part of it can be spent, for example, for the production of electrical energy to external consumers, which will facilitate the commercialization of this development. Thus, in the variant proposed, the processing technology corresponds well to the general idea of numerous publications in the world literature, known as the Waste-to-Energy.

It should be emphasized that the sensitivity of the estimates has been obtained from the selected composition of carbon-containing gasified raw materials. Therefore, further development of these studies requires variation of this composition, as well as more strictly quantitative fraction of the mineral component of the sewage sludge. The same applies to other types of hazardous waste. This part of the publication is the methodological basis for such an analysis. In accordance with this, the role of the plasma part of the technology can also increase or, conversely, decrease. Nevertheless, especially for multi-purpose installations, its role from the point of view of the environmental safety of the process remains unchanged.

5. The state of design and construction of the shaft reactor for waste treatment plant based on plasma-steam-oxygen technology

5.1. Features of the project

In 2017, the Institute of Gas of the National Academy of Sciences of Ukraine completes the execution of the state order for development of steam-plasma technology for the processing of sewage sludge with the support of the Ministry of Education and Science of Ukraine. The result will be a reactor module for waste treatment based on plasma-steam-oxygen technology, which can become the core of plants for the recycling of hazardous waste: bottom sediments of aeration stations of urban water purification systems, unsorted solid household wastes (they are dangerous because of the risk of entering into their composition of chlorinated compounds), medical waste, overdue pesticides and chemical treatments for plants, etc. The module is designed in such a way as to ensure its payback through the production of electrical energy through the products of gasification of carbon compounds in the waste. At the heart of the implementation of this project lie precisely the above calculations.

Unlike the previous development [9], the peculiarity of this shaft reactor is the loading of raw materials through its side wall. This will allow, on the one hand, to comply with the operating mode of the reactor, which meets the requirements of the Directive 2000/76/EC [15] for the processing of chlorine-containing waste. On the other hand, the operation of the PT will contribute to the achievement of the temperature regime characteristic for the vitrification of the ash residue, thus solving the problem of handling wastes containing heavy metals. The reactor capacity will be up to 500 kg/h depending on the type of waste. In terms of annual capacity, this will be up to 4000 tons per year, based on the 11-month cycle of work. The reactor will be tested this year, completely with equipment previously developed as part of a medical waste treatment plant [9]. The general view of the reactor of this plant is shown in **Figure 5**.

Researchers of LEI are also projecting a novel plasma volume reactor (**Figure 6**) to create steady non-transferred plasma ambient. It will allow the destruction wide range of hazardous substances.

The primary shield of the reactor is made up of steel (1500 mm of height × 1500 mm of width) with high temperature ceramic inner lining. Initially, it has hopper for waste feeding with single door arrangement. The door operation is manual. The chamber has several ports, 350 mm above the bottom of the chamber for mounting air or nitrogen PT. It is expected the plasma arc reactor have very high destruction efficiency and will be very robust. It is considered that it will be able to treat any waste with minimal or no pretreatment and produce a single waste form as gas and slag. The designed arc reactor has carbon anode and will strike an arc in a bath of molten slag. The higher temperatures will be reached by the arc convert the organic waste into light organics and primary elements. The system is under further development.

5.2. Economic assessments

Estimated construction cost of the plant for processing hazardous waste using the proposed reactor module will be about 1.2 million USD. If we compare it with the data of the publication

Figure 5. The reactor module body for plasma-steam-oxygen waste treatment in the stage of its installation.

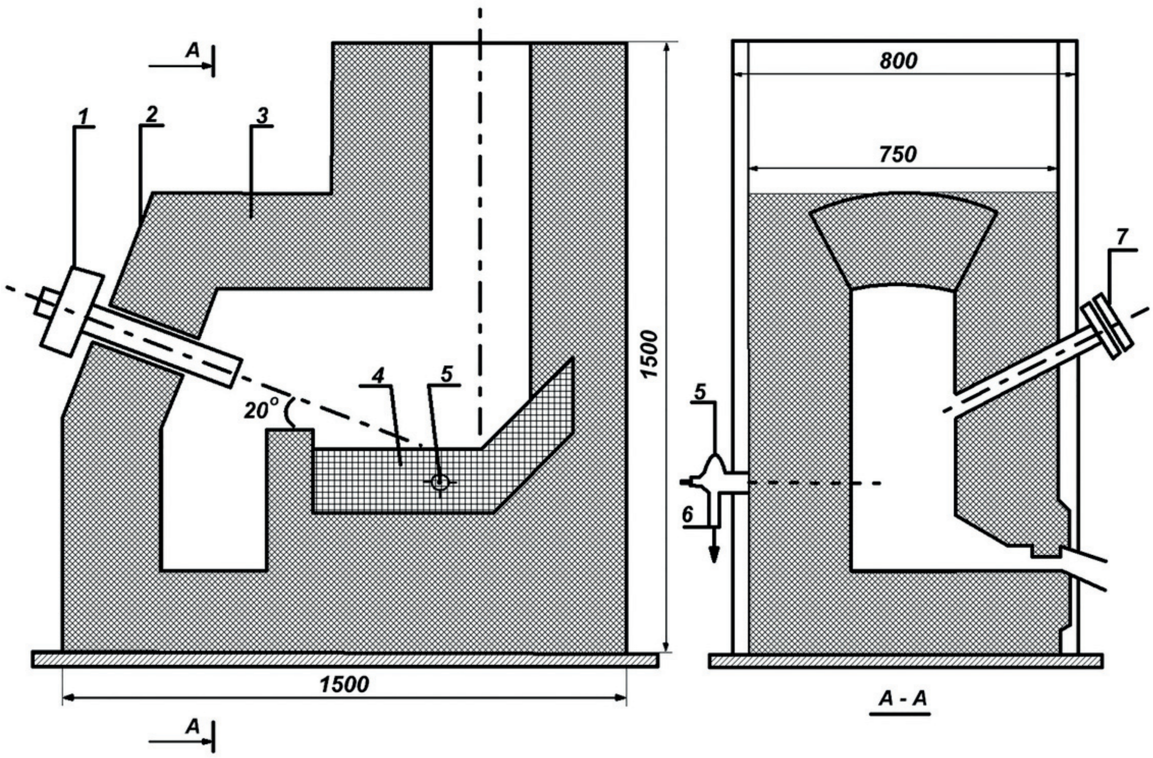

Figure 6. Plasma arc reactor. 1—Plasma torch; 2—Metallic shield; 3—Lining alloy; 4—Graphite plate; 5—Circular channel; 6—Observation window.

Youngchul Byun et al. [7], in terms of present value to the daily capacity of the reactor 12 TPD, this is noticeably less. The latter is due to the low cost of labor in present-day Ukraine. The estimates obtained in this article make it possible to compare its economic indicators with other developments presented in the Ukrainian market, among them, Waste-to-Energy Plant "Energy-2" from Brno [34], Integrated Multifuel Gasification technology (IMG) of Bellwether Recuparative Gasification Ltd. [35] and Westinghouse Plasma Corporation [36]. **Table 7** shows the main technical and economic indicators that characterize the operation of these plants according to the references given. These include: C—annual capacity of equipment (t/a), P—power generation of electricity to consumers per year (MW·h/a), I—investments. As can be

Indicator	Technology			
	"Energy-2" [34]	**IMG [35]**	**WPC [36]**	**IG NASU (project, this paper)**
C, t/a	224,000	100,000	534,000	4000
P, MW·h/a	63,000	68,000	427,000	4200
I, USD(€)	130 mln. €	65 mln. €	307.5 mln. USD	**1.2** mln. USD
I/C, USD(€)/t	580	650	575	300
P/C, kW·h /t	240	680	800	1050
Payback (in the absence of operating costs), years	61.9	28.7	20	8

Table 7. Comparison of the main technical and economic indicators of some waste-processing plants in Ukraine (see explanation in the text).

seen, the traditional waste-processing plant [34] “Energy-2” requires specific investments I/C, close to the plasma technologies [35, 36]. On the contrary, it has the worst indicators P/C concerning the possibility of investment return due to the production of additional electric energy for external consumers. All three samples of technologies [34–36] have a very high cost; it cannot be compensated by production of additional electric energy. Some additional reduction of payback is achieved by the presence of a “green tariff” in Ukraine for electric energy.

Thus, the proposed plasma-steam-oxygen technology of waste treatment has the highest calculated efficiency indicators compared with the developments under discussion. At the same time, it provides high levels of environmental safety. Further to improve the efficiency of this technology, it can facilitate the transition to more efficient methods of electricity production from syngas obtained [13]. This will lead to increasing value η_{EE} and, respectively, further decrease of the part of synthesis gas that is used for energy self-sufficiency of gasification equipment. Such prospects are associated primarily with fuel cell technology that has significantly greater efficiency than gas-diesel power stations.

6. Conclusion

Contrary to popular belief among experts in classical thermal physics, the process of plasma gasification, even in the absence of oxygen blasting, can be maintained in the regime of energy self-sufficiency.

The most general assessments of ecological benefits and energy efficiency of plasma-steam gasification technologies are presented. It is shown based on the thermodynamic study that processing of sewage sludge using plasma technologies can be commercially attractive.

The described hazards treatment system has the ability to accept a wide range of waste materials and as such can be regarded as a mobile and flexible treatment system. This system can be applied to treat high toxic wastes containing both organic and inorganic substances.

The results show that hazards treatment technology can process highly toxic organic and inorganic substances with the efficiency of 99.99%.

The results on heat balance and heat transfer point that the combustion process takes place over all the reactor volume. The incineration process finishes through the entrance section ($x/d < 1$) of the reactor chamber.

Acknowledgements

The study one of the authors (V. Zhovyansky) was supported by Ministry of Education and Science of Ukraine, project “The development of steam-plasma technology of aeration stations sewage sludge conversion” and the National Academy of Sciences of Ukraine, programs “Prospective study of plasma physics, controlled thermonuclear fusion and plasma technology” and “Basic aspects of renewable-hydrogen power and fuel cell technology”.

Author details

Victor Zhovtyansky[1] and Vitas Valinčius[2]*

*Address all correspondence to: vitas@mail.lei.lt

1 Institute of Gas of the National Academy of Sciences of Ukraine, Kyiv, Ukraine

2 Lithuanian Energy Institute, Kaunas, Lithuania

References

[1] Gorokhovski M, Karpenko EI, Lockwood FC, Messerle VE, Trusov BG, Ustimenko AB. Plasma technologies for solid fuels: Experiment and theory. Journal of the Energy Institute. 2000;**78**(4):157-171

[2] Rutberg PG. Plasma pyrolysis of toxic waste. Plasma Physics and Controlled Fusion. 2003;**45**:957-969

[3] Chernets OV, Korzhyk VM, Marynsky GS, Petrov SV, Zhovtyansky VA. Electric arc steam plasma conversion of medicine waste and carbon containing materials. In: Jones JE, editor. Proceedings of XVII GD; 7–12 September, 2008; Cardiff, Wales: Cardiff University; 2008. pp. 465-468

[4] Hrabovsky M, Hlina M, Konrad M, Kopecky V, Kavka T, Chumak O, Maslani A. Thermal plasma gasification of biomass for fuel gas production. Journal of High Temperature Material Processes. 2009;**13**(3–4):299-313

[5] Ducharne C. Technical and economic analysis of Plasma-assisted Waste-to-Energy processes. Earth Engineering Centre, Columbia University. 2010. p. 50

[6] Brattsev AN, Kuznetsov VA, Popov VE, Ufimtsev AA. Arc gasification of biomass: Example of wood residue. High Temperature. 2011;**49**:244-248

[7] Byun Y, Cho M, Hwang S-M, Chung J. Thermal plasma gasification of municipal solid waste (MSW). In: Yun Y, editor. Gasification for Practical Applications. Rijeka, Croatia: InTechOpen; 2012. pp. 183-210

[8] Zhang Q, Dor L, Fenigshtein D, Yang W, Blasiak W. Gasification of municipal solid waste in the plasma gasification melting process. Applied Energy. 2012;**90**:106-112

[9] Zhovtyansky VA, Petrov SV, Lelyukh YI, Nevzglyad IO, Goncharuk YA. Efficiency of renewable organic raw materials conversion using plasma technology. IEEE Transactions on Plasma Science. 2013;**41**(12):3233-3239

[10] Fabry F, Rehmet C, Rohani V-J, Fulcheri L. Waste gasification by thermal plasma: A review. Waste and Biomass Valorization. 2013;**4**(3):421-439. DOI: 10.1007/s12649-013-9201-7

[11] Tamosiunas A, Valatkevicius P, Valincius V, Levinskas R. Biomass conversion to hydrogen-rich synthesis fuels using water steam plasma. Comptes Rendus Chimie. 2016; **19**:433-440. DOI: 10.1016/j.crci.2015.12.002

[12] Messerle VE, Mosse AL, Ustimenko AB. Municipal solid waste plasma processing: Thermodynamic computation and experiment. IEEE Transactions on Plasma Science. 2016; **44**(12):3017-3022

[13] Zhovtyansky VA, Kolesnikova EP, Yakymovych MV. Plasma-assisted waste-to-energy processes. Problems of Atomic Science and Technology. 2017;**1**(107):231-236

[14] Striugas N, Valincius V, Pedisius N, Poskas R, Zakarauskas K. Investigation of sewage sludge treatment using air plasma assisted gasification. Waste Management. 2017;**64**: 149-160. DOI: 10.1016/j.wasman.2017.03.024

[15] Council of the European Union. Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration waste. Official Journal of the European Communities. JOL. 2000;**L 332**:91-111. CELEX: 32000L0076

[16] Official Journal of the European Communities. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2008:0030:FIN:en:PDF

[17] Gomez E et al. Thermal plasma technology for the treatment of wastes: A critical review. Journal of Hazardous Materials. 2009;**161**(2–3):614-626

[18] Materazzi M et al. Tar evolution in a two stage fluid bed–plasma gasification process for wastevalorization. Fuel Processing Technology. 2014;**128**:146-157

[19] McGrath S. Persistent organic pollutants and metals from sewage sludge: Their effects, on soil plants and food chain. In: Langenkamp H, Marmo L, editors. Workshop on Problems Around Sewage Sludge; 18–19 November, 1999; Italy Proceedings-European Commissions Joint Research Center; 2000. p. 242

[20] Balgaranova J. Plasma chemical gasification of sewage sludge. Waste Management & Research. 2003;**21**:38. DOI: 10.1177/0734242X0302100105

[21] Cedzynska K, Kolacinski Z, Izydorczyk M, Sroczynski W. Plasmavitrification of waste incinerator ashes. In: International Ash Utilization Symposium; Centre for Applied Energy Research; 1999

[22] Valinčius V, Krušinskaitė V, Valatkevičius P, Valinčiūtė V, Marcinauskas L. Electric and thermal characteristics of the linear, sectional DC plasma generator. Plasma Sources Science and Technology. 2004;**13**(2):199-206. ISSN 0963–0252

[23] Zhukov MF, Zasypkin IM. Thermal Plasma Torches: Design, Characteristics, Applications. United Kingdom: Cambridge International Science Publishing; 2007. 596p

[24] Solonenko OP. Thermal Plasma Torches and Technologies. Cambridge International Science Publishing; 2000. 410p

[25] Snapkauskienė V, Valinčius V, Valatkevičius P. Heat transfer in the arc discharge channel. Heat Transfer Research. 2009;**40**(5):399-413. ISSN 1064-2285

[26] Leal-Quiros E. Plasma processing of municipal solid waste. Brazilian Journal of Physics. 2004;**34**(4B):1587-1593

[27] Ravich M.B. Efficiency of fuel use. Moscow: Nauka; 1977. 258p

[28] Prigozhin I, Kondepudi D. Modern Thermodynamics. From Heat Engines to Dissipative Structures. Moscow: Mir; 2002. 461p

[29] Zhovtyansky VA, Orlyk VM, Petrov SV, Yakymovych MV. General principles of waste treatment with recycling their energy potential based on plasma technology. Part I. Ecological requirements, the thermodynamics of the process and its energy efficiency. Energy Technologies and Resources. 2015;**4**:24-46

[30] McAllister S, Chen JY, Fernandez-Pello AC. Fundamentals of Combustion Processes (Mechanical Engineering Series). New York: Springer Science and Business Media; 2011. DOI: 10.1007/978-1-4419-7943-8_2

[31] Mountouris A, Voutsas E, Tassios D. Solid waste plasma gasification: Equilibrium model development and exergy analysis. Energy Conversion and Management. 2006;**47**:1723-1737

[32] Vatolin NA, Moiseev GK, Trusov BG. Thermodynamic Modelling of High-Temperature Inorganic Systems. Moscow: Metallurgy; 1994. 353p

[33] Zhovtyansky VA, Orlyk VM, Petrov SV, Yakymovych MV. General principles of waste treatment with recycling their energy potential based on plasma technology. Part II. Gasification of sewage sludge from water treatment plants. Energy Technologies and Resources. 2016;**3**:25-42

[34] Technical Overview of the Waste-to-Energy Plant in Brno, Plant for Region with 2 mil. People [Internet]. [Updated: 2017]. Available from: http://www.sako.cz/page/en/607/waste-to-energy/

[35] Integrated Multifuel Gasification Technology (IMG) of Bellwether Recuparative Gasification Ltd [Internet]. [Updated: 2017]. Available from: http://bwrs.eu/

[36] Technology of Plasma Gasification Westinghouse Plasma Corporation [Internet]. [Updated: 2016]. Available from: http://www.cleandex.ru/articles/2016/03/07/zavody_po_pererabotke_othodov_proizvodstva_i_potrebleniya_v_elektroenergiyu